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OPTIMAL TRADING PARTNERS SELECTION STRATEGY AND TRANSACTIVE ENERGY MECHANISM OF VIRTUAL POWER PLANT

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ABSTRACT

Wind generators (WGs) may suffer from heavy imbalance costs caused by their uncertainty nature if they bid in electricity market independently. However, they can utilize demand response (DR) potential of flexible loads like air conditioners (ACs) to set off their power fluctuation. In this paper, WGs joint with ACs constitute a virtual power plant (VPP), and bid in the market as a whole. Transactive energy (TE) serves as the main approach to setting off power deviations of distributed energy resources (DERs) including WGs and ACs, through deviation energy trading among them. An optimal day-ahead strategy is proposed for VPP operator (VPPO) to select qualified trading partners for WGs based on their transaction demand. Then VPPO sets up real-time TE market inside the coalition and launches double auctions (DAs) in each time slot of the next day, inducing DERs to set off their power deviations through peer to peer (P2P) energy trading. Results of case study show that VPPO can select qualified trading partners for WGs efficiently, maximizing VPP's prospective revenue as well as covering WGs' transaction demand. Both DERs and VPPO can benefit from TE market without sacrificing AC consumers' comfort.

Keywords: demand response, distributed energy resource, double auction, transactive energy, virtual power plant

NONMENCLATURE

Symbols	
$\omega_{i,t}^{WL} / \omega_{i,t}^{WU}$	lower/upper bound of confidence interval
R / C	equivalent thermal resistance and capacitance
T^{in} / T^{out}	indoor and outdoor temperature
P^{AC}	AC's power
EER	cooling energy efficiency ratio
ζ	consumer's comfort
T^{des}	consumer's desired temperature
δ	largest temperature deviation
$P^{AC,min} / P^{AC,max}$	AC's minimum and maximum power
c	cost of consumers' comfort loss
F	function of power consumed by AC
R_t^{up} / R_t^{down}	WGs' Reg-up/ Reg-down demand
$P_{i,t}^{W,pre} / P_{i,t}^{W}$	WG's forecast/actual power
Γ^{DA}	VPP's prospective profit
$P_t^{VPP,DA}$	VPP's day-ahead bidding power
$\rho_t^{DA} / \rho_t^{RT}$	day-ahead/real-time electricity price
β_j	consumer's declared electricity price discount ratio
$P_t^{W,+} / P_t^{W,-}$	power deviation when real-time power is beyond lower or upper bound of confidence interval
$\lambda_t^{+} / \lambda_t^{-}$	punishment ratios of power insufficiency and surplus
γ	unit price ratio for wind generation

$P_{j,t}^{\mathrm{AC,pre}} / P_{j,t}^{\mathrm{AC}}$	AC's scheduled/actual power
$P_{j,t}^{\mathrm{AC,N}}$	AC's unscheduled power
υ_j	binary variable denoting AC's selected status
$P_{\mathrm{a}}/P_{\mathrm{f}}$	actual/forecast power data
$P_{t,m}^{\mathrm{b,-}} / P_{t,m}^{\mathrm{b,+}}$	Reg-down/up bidding amount as a buyer
$P_{t,m}^{\mathrm{s,-}} / P_{t,m}^{\mathrm{s,+}}$	Reg-down/up bidding amount as a seller
$P_{t,l}^{\mathrm{b,-}} / P_{t,l}^{\mathrm{b,+}}$	Reg-down/up turnover as a buyer
$P_{t,l}^{\mathrm{s,-}} / P_{t,l}^{\mathrm{s,+}}$	Reg-down/up turnover as a seller
$\pi_{t,m}^{\mathrm{b,-}} / \pi_{t,m}^{\mathrm{b,+}}$	bidding price for power Reg-down/up as a buyer
$\pi_{t,m}^{\mathrm{s,-}} / \pi_{t,m}^{\mathrm{s,+}}$	bidding price for power Reg-down/up as a seller
$\Pi_{j,t,m}^{\mathrm{ADJ}}$	AC's power adjustment profit
β_{in}	discount ratio of price for electricity transferred from power surplus DER to power insufficiency DER

1. INTRODUCTION

Power system has encountered frequent power imbalance problems in recent years with great penetration of DERs. AC, as a typical flexible load, can adjust its power consumption in DR programs to set off power fluctuation of distribution generators (DGs), maintaining balance of power system. DERs with enormous flexibility potential like ACs desire a market which can give access to them so that they can achieve their market values through energy trading.

TE is "*a set of economic and control mechanisms that allow the dynamic balance of supply and demand across the entire electrical infrastructure using value as a key operational parameter*" [1], targeting distributed market entities at distribution level, which completely caters to the distributed feature of DERs. Induced by price signals, buyers and sellers can interact with each other directly in a completely decentralized framework, which can maintain dynamic balance of supply and demand.

WGs have transaction demands when there exists difference between actual and forecasted output. Correspondingly, ACs own transaction capabilities because of their DR potential. VPPO can aggregate various DERs and behave as a market entity [2] to effectively hedge risks brought about by uncertainty for that power fluctuation of DERs can be set off by energy trading inside the coalition. It should be emphasized that VPPO must provide electricity fees subsidies for ACs to obtain control over them.

Lots of research on VPP and TE has been conducted at both home and abroad until now. However, the decentralization of distributed energy trading among DERs inside VPP is not achieved yet. Within the above context, the main contributions of this paper are twofold:

1) Propose an optimal strategy to select qualified trading partners for WGs in TE market, considering ACs' subsidy costs and transaction capabilities.

2) Launch DAs in TE market to set off DERs' power deviation inside VPP, hedging risks from real-time balancing market, which can benefit both VPPO and DERs.

2. MODELS AND CHARACTERISTICS OF DERS INSIDE VPP

2.1 Basic model of WG and AC

Actual wind power output falls in the interval with a certain confidence level, which could lead to a deviation from forecast data [3]. The first order equivalent thermal parameters (ETP) model of an air conditioner room is given in [4].

2.2 DR potential of AC considering consumer's comfort

Consumer's comfort is defined as follows.

$$\zeta = \frac{T^{\mathrm{des}} - T^{\mathrm{in}}}{\delta} \tag{1}$$

Combining (1) and ETP model of AC room in [4], AC's power to maintain consumer's comfort at ζ can be calculated as follows.

$$P^{AC} = \left(\delta \cdot \zeta + T^{\mathrm{out}} - T^{\mathrm{des}}\right) / \left(R \cdot EER\right) \tag{2}$$

Consumers set AC power limits based on their comfort demand, which is limited within [-2,2] in normal operation settings.

2.3 Price-function elasticity of AC

Power adjustment cost of ACs [5] is defined as

$$\Delta c = c_0 \cdot \Delta F / F_0 \tag{3}$$

where subscript 0 denotes the original value and Δ denotes the value's variation.

3. QUALIFIED TRADING PARTNERS SELECTION STRATEGY

TE is the main approach to coping with wind power's uncertainty in this paper, so there should exist trading partners for WGs. Since ACs have transaction capabilities, they desire electricity fees discount if their

DR potential is utilized to set off wind power's fluctuation. VPPO, representing WGs clusters, selects qualified ACs as WGs' trading partners, considering ACs' transaction capabilities and their desired discount ratios. Then VPPO schedules ACs' power day ahead according to WGs' forecast data confidence interval.

3.1 WGs' transaction demands for trading partners

WGs trade their power deviations induced by real-time power scenarios within confidence interval; otherwise, they will leave the deviations to be coped with in the balancing market. WGs' transaction demands are calculated as

$$\begin{cases} R_t^{\mathrm{up}} = \sum_{i \in I} \int_{x=\omega_{i,t}^{WL}}^{x=P_{i,t}^{\mathrm{pre}}} \left(P_{i,t}^{\mathrm{W,pre}} - x \right) f_p\left(P_{i,t}^{\mathrm{W}} \right) \mathrm{d}x, \quad \forall t \in T \\ R_t^{\mathrm{down}} = \sum_{i \in I} \int_{x=P_{i,t}^{\mathrm{pre}}}^{x=\omega_{i,t}^{WU}} \left(x - P_{i,t}^{\mathrm{W,pre}} \right) f_p\left(P_{i,t}^{\mathrm{W}} \right) \mathrm{d}x, \ \forall t \in T \end{cases} \tag{4}$$

3.2 Qualified trading partners selection strategy

VPPO selects qualified trading partners for WGs, as well as determines the best confidence interval bounds of wind power forecast data and the scheduled power of selected ACs in the next day. The profit maximization problem is formulated as follows. Five elements in (5) represent VPP's prospective revenue for bidding in day-ahead market, VPP's prospective revenue for providing the selected ACs with power supply at a certain discount declared by consumers, VPP's payment to WGs for wind power purchase, VPP's imbalanced cost caused by wind power insufficiency when real-time power is beyond the lower bound of confidence interval and VPP's imbalanced cost caused by wind power surplus when real-time power is beyond the upper bound of confidence interval respectively.

$$\begin{aligned} \max_{\omega_{i,t}^{WL}, \omega_{i,t}^{WU}, \upsilon_{j,t}, P_{j,t}^{\mathrm{AC,pre}}} \Gamma^{\mathrm{DA}} = & \sum_{t \in T} P_t^{\mathrm{VPP,DA}} \rho_t^{\mathrm{DA}} \Delta t + \sum_{j \in J} \sum_{t \in T} P_{j,t}^{\mathrm{AC,pre}} \beta_j \rho_t^{\mathrm{DA}} \Delta t \\ & - \sum_{j \in J} \sum_{t \in T} P_t^{\mathrm{W,+}} \lambda_t^{+} \rho_t^{\mathrm{DA}} \Delta t - \sum_{j \in J} \sum_{t \in T} P_t^{\mathrm{W,-}} \lambda_t^{-} \rho_t^{\mathrm{DA}} \Delta t \\ & - \sum_{i \in I} \sum_{t \in T} P_{i,t}^{\mathrm{W,pre}} \gamma \rho_t^{\mathrm{DA}} \Delta t \end{aligned}$$

s.t. (5)

(1) Transaction demands constraint

$$\begin{cases} \sum_{j \in J} \left(P_{j,t}^{\mathrm{AC,pre}} - \upsilon_j P_{j,t}^{\mathrm{AC,min}} \right) \geq R_t^{\mathrm{up}}, \quad \forall t \in T \\ \sum_{j \in J} \left(\upsilon_j P_{j,t}^{\mathrm{AC,max}} - P_{j,t}^{\mathrm{AC,pre}} \right) \geq R_t^{\mathrm{down}}, \ \forall t \in T \end{cases} \tag{6}$$

(2) ACs' electric bills constraint

$$\sum_{t \in T} P_{j,t}^{\mathrm{AC,pre}} \beta_j \rho_t^{\mathrm{DA}} \Delta t \leq \sum_{t \in T} P_{j,t}^{\mathrm{AC,N}} \rho_t^{\mathrm{DA}} \Delta t, \ \forall j \in J \tag{7}$$

(3) ACs' power limits constraint

$$\upsilon_j P_j^{\mathrm{AC,min}} \leq P_{j,t}^{\mathrm{AC,pre}} \leq \upsilon_j P_j^{\mathrm{AC,max}}, \ \forall j \in J, t \in T \tag{8}$$

(4) Power balance constraint

$$P_t^{\mathrm{VPP,DA}} = \sum_{i \in I} P_{i,t}^{\mathrm{W,pre}} - \sum_{j \in J} P_{j,t}^{\mathrm{AC,pre}}, \ \forall t \in T \tag{9}$$

4. REAL-TIME TE MECHANISM INSIDE VPP

4.1 Distributed imbalance trade in TE mechanism

TE market inside VPP is essentially a distributed imbalance trade market, in which buyers have demand for power regulation up or down (Reg-up or Reg-down), meanwhile sellers have ability of power Reg-up or Reg-down. For generators, Reg-up demand means that their actual power generation is lower than the forecast data; for loads, Reg-up demand means that their actual power consumption is higher than the forecast data. In this paper, WGs and ACs can serve as both buyers and sellers. Their trade status and corresponding bidding forms are shown in Table 1.

Table 1

Trade status and bidding forms of DERs

Power Deviation	WG	AC
$P_a > P_f$	Reg-down buyer, + Reg-up seller, -	Reg-up buyer, + Reg-down seller, -
$P_a < P_f$	Reg-up buyer, + Reg-down seller, -	Reg-down buyer, + Reg-up seller, -
$P_a = P_f$	NA	Reg-down seller, + Reg-up seller, +

In Table 1, P_a and P_f denote actual and forecast power data respectively. '+' and '-' are the signs of DERs' bidding price. The bidding price is minus when DERs serve as sellers in the situation where there exists deviation between actual and forecast power.

4.2 Continuous Double Auction Process in TE Market

In continuous DA mechanism, buyers and sellers can bid in the market at any time during a trade period. The auctioneer ranges buyers' and sellers' bidding prices in a descend and ascend sequence respectively, then matches buyers and sellers according to the sequence of their bidding prices. The matched pair can trade with each other, taking average of both sides' bidding prices as the deal price [6].

4.3 Bidding strategies of DERs during DA process

VPPO, serving as an auctioneer, launches DAs in real-time TE market. DERs' power deviation thus can be set off through peer to peer trade inside VPP.

4.3.1 Bidding strategies of WGs

We take the situation where $P_a > P_f$ for example to analyze WGs' bidding strategies in this section.

(1) Reg-down buyer

WG's bidding amount in the *m*th DA round is depicted as

$$P^{b,-}_{i,t,m} = P^{W}_{i,t} - P^{W,pre}_{i,t} - \sum_{l=1}^{m-1} P^{b,-}_{i,t,l}, \quad P^{W}_{i,t} > P^{W,pre}_{i,t} \tag{10}$$

WG's bidding price is subject to the limit

$$\pi^{b,-}_{i,t,m-1} \le \pi^{b,-}_{i,t,m} \le \lambda_t^- \rho_t^{RT} \tag{11}$$

(2) Reg-up seller

WG's bidding amount in the *m*th DA round is depicted as

$$P^{s,+}_{i,t,m} = P^{W}_{i,t} - P^{W,pre}_{i,t} - \sum_{l=1}^{m-1} P^{s,+}_{i,t,l}, \quad P^{W}_{i,t} > P^{W,pre}_{i,t} \tag{12}$$

WG's bidding price is subject to the limit

$$-\lambda_t^- \rho_t^{RT} \le \pi^{s,+}_{i,t,m} \le \pi^{s,+}_{i,t,m-1} \le 0 \tag{13}$$

4.3.2 Bidding strategies of ACs

ACs' bidding strategies are similar to those of WGs when $P_a > P_f$ and $P_a < P_f$. Thus we only analyze ACs' bidding strategies when $P_a = P_f$ in this part.

(1) Reg-up seller

AC's local optimization problem can be formulated as follows.

$$\max_{P^{s,+}_{j,t,m}} \Pi^{ADJ}_{j,t,m} = P^{s,+}_{j,t,m}\pi^{s,+}_{j,t,m} + P^{s,+}_{j,t,m}\beta_j \rho_t^{RT} - P^{s,+}_{j,t,m} c_0 \left|\zeta_{j,t,m}\right| / \left|\zeta_j^{max}\right| \tag{14}$$

s.t.

$$\zeta_j^{min} \le \zeta_{j,t} \le \zeta_j^{max} \tag{15}$$

$$0 \le P^{s,+}_{j,t,m} \le P^{AC}_{j,t} - P^{AC,min}_{j} - \sum_{l=1}^{m-1} P^{s,+}_{j,t,l} \tag{16}$$

(2) Reg-down seller

AC's local optimization problem can be formulated as follows.

$$\max_{P^{s,-}_{j,t,m}} \Pi^{ADJ,-}_{j,t,m} = P^{s,-}_{j,t,m}\pi^{s,-}_{j,t,m} - P^{s,-}_{j,t,m}\beta_j \rho_t^{RT} - P^{s,-}_{j,t,m}\left(c_0 \left|\zeta_{j,t,m}\right| / \left|\zeta_j^{max}\right| + \beta_{in}\rho_t^{RT}\right) \tag{17}$$

s.t.

$$\zeta_j^{min} \le \zeta_{j,t} \le \zeta_j^{max} \tag{18}$$

$$0 \le P^{s,-}_{j,t,m} \le P^{AC,max}_{j} - P^{AC}_{j,t} - \sum_{l=1}^{m-1} P^{s,-}_{j,t,l} \tag{19}$$

Dynamic Hurwicz strategy [7] is utilized in this paper to update the bidding prices of both sides.

5. CASE STUDY

VPPO selects trading partners for 50 WGs in the range of 200 ACs day ahead and launches real-time DAs to set off deviation between VPP's actual output and the bidding output.

5.1 *Trading Partners Selection Results*

VPPO determines the best confidence intervals of wind power forecast data by making tradeoffs between underlying imbalance cost and ACs' electricity subsidies. The results are shown in Fig 1.

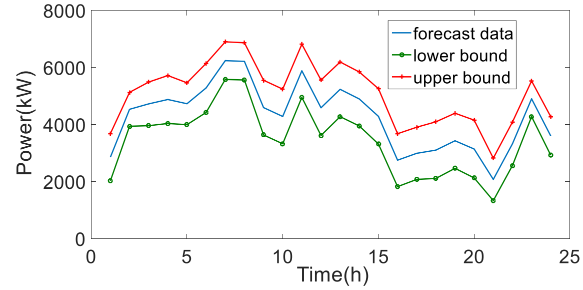

Fig 1 Best confidence interval of wind power forecast data

The selection results are shown in Fig 2, where blue bars represent selected status of ACs, while red line stands for ACs' desired discount ratios. It can be seen that most ACs selected by VPPO feature high discount ratio ranging from 0.8 to 1.0 for the reason that VPPO can provide these ACs with less subsidies. Nevertheless, there also exist seven ACs in the selected range in spite that their desired discount ratios are less than 0.8, because they have high transaction capabilities.

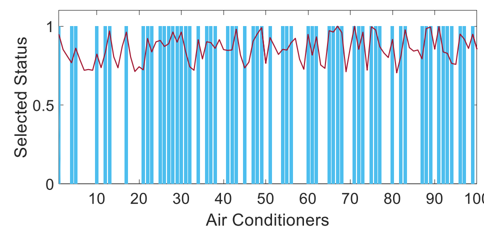

Fig 2 ACs selection results

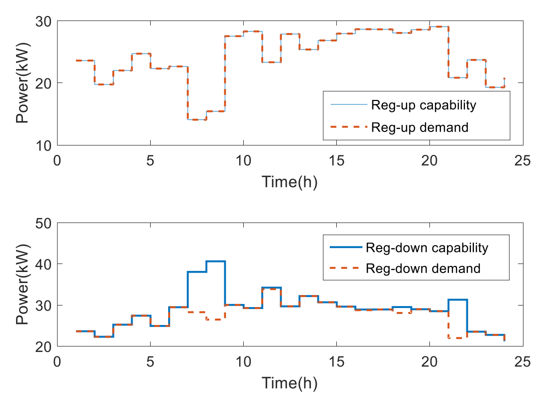

Fig 3 Transaction demands and capabilities

DERs' transaction demands and capabilities are shown in Fig 3. It is clear that the Reg-up capabilities of ACs are exactly equal to the demands of WGs, whereas there exist surplus in Reg-down capabilities. Because VPPO tends to schedule ACs' working points by the lower limits to maximize profit, as long as consumers' comfort can be guaranteed.

5.2 Trade results in TE market

Trade results in TE market in the 14th time slot are analyzed in this section. Power deviations of DERs with and without TE are presented in Fig 4.

We can see that power deviation of 18 WGs and 5 ACs are completely eliminated in TE market. However, deviation of the 8th WG is only set off by 19.8kW because its bidding price is extremely low as a Reg-up buyer.

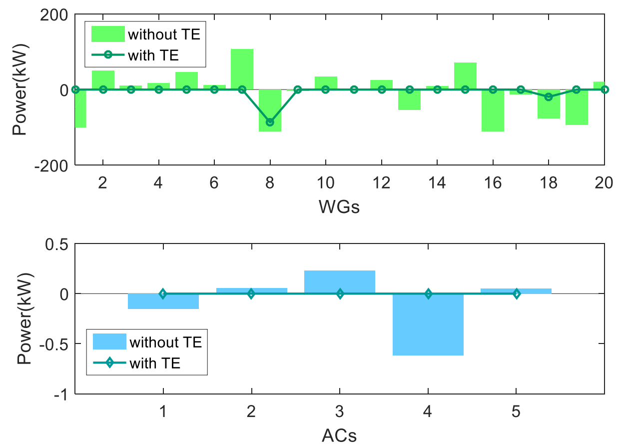

Fig 4 Power deviations of DERs with and without TE

Costs and revenues of DERs in TE market are shown in Fig 5.

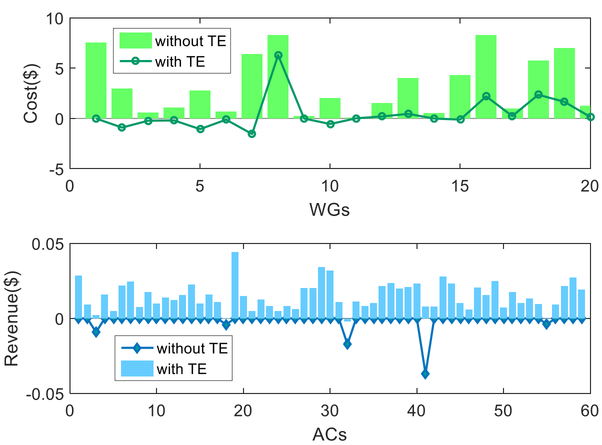

Fig 5 Costs and revenues of DERs

It is shown that imbalance costs of all DERs decrease through energy trading, some of which even obtain extra revenue.

5.3 VPP's real-time operating results

VPP's real-time power output is presented in Fig 6. It can be summarized that VPP's real-time output almost coincides with the bidding curve when there is a TE market inside VPP, which can effectively reduce imbalance cost in real-time balancing market.

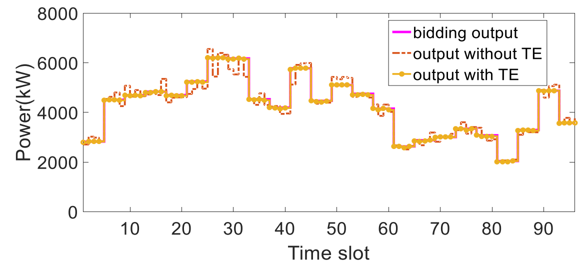

Fig 6 VPP's power output curves

VPP's revenue is shown in Fig 7. We can clearly see that VPP's revenue increases in every time slot on condition that DERs' power deviations are set off in TE market.

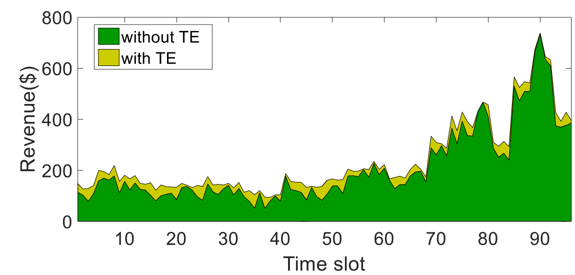

Fig 7 VPP's revenue

5.4 Consumers' comfort

In Fig 8, the dots represent consumers' comfort values.

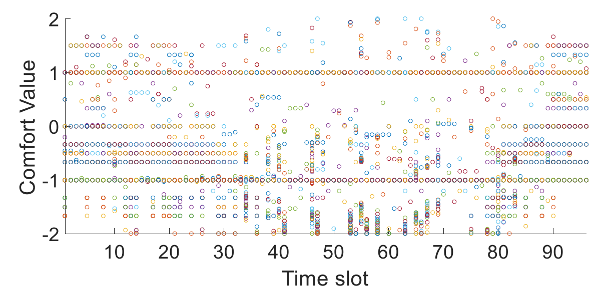

Fig 8 Consumers' comfort

It is depicted in Fig.10 that comfort values are maintained within [-2,2], which is the comfort limit declared by consumers. Thus the strategy proposed in this paper can completely satisfy consumers' comfort demand.

6. CONCLUSION

Results of case study show that: 1) VPPO tends to select ACs with high discount ratios and transaction capabilities as qualified trading partners of WGs. 2) The strategy can benefit all traders as well as the organizer in TE market. 3) The strategy can reduce VPP's actual output deviation comparing with the day-ahead bidding output. 4) The strategy can maintain consumers' comfort values within the declared limits, which is consumer-friendly.

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